THE ASTROPHYSICAL JOURNAL, 526:L000–L000, 1999 November 20
© 1999. The American Astronomical Society. All rights reserved. Printed in U.S.A.

A NEW SUPERNOVA REMNANT COINCIDENT WITH THE SLOW X-RAY PULSAR AX J1845−0258

B. M. GAENSLER,[1,2] E. V. GOTTHELF,[3] AND G. VASISHT[4]

Received 1999 July 26; accepted 1999 September 24; published 1999 October 00

ABSTRACT

We report on Very Large Array observations in the direction of the recently discovered slow X-ray pulsar AX J1845−0258. In the resulting images, we find a 5′ shell of radio emission; the shell is linearly polarized with a nonthermal spectral index. We classify this source as a previously unidentified, young (<8000 yr) supernova remnant (SNR), G29.6+0.1, which we propose is physically associated with AX J1845−0258. The young age of G29.6+0.1 is then consistent with the interpretation that anomalous X-ray pulsars (AXPs) are isolated, highly magnetized neutron stars ("magnetars"). Three of the six known AXPs can now be associated with SNRs; we conclude that AXPs are young ($\lesssim$10,000 yr) objects and that they are produced in at least 5% of core-collapse supernovae.

Subject headings: ISM: individual (G29.6+0.1) — pulsars: individual (AX J1845−0258) — radio continuum: ISM — stars: neutron — supernova remnants — X-rays: stars

1. INTRODUCTION

It is becoming increasingly apparent that isolated neutron stars come in many flavors besides traditional radio pulsars. In recent years, the neutron star zoo has widened to include ∼10 radio-quiet neutron stars (Brazier & Johnston 1999), six anomalous X-ray pulsars (AXPs; Mereghetti 1999), and four soft γ-ray repeaters (SGRs; Kouveliotou 1999). There is much uncertainty and debate as to the nature of these sources; one way to characterize their properties is through associations with supernova remnants (SNRs). An association with a SNR gives an independent estimate of a neutron star's age and distance, while the position of the neutron star with respect to the SNR's center can be used to estimate the transverse space velocity of the compact object.

The AXPs are case in point. Some authors propose that the AXPs are accreting systems (van Paradijs, Taam, & van den Heuvel 1995; Mereghetti & Stella 1995; Ghosh, Angelini, & White 1997), while others argue that AXPs are "magnetars," isolated neutron stars with very strong magnetic fields, $B \gtrsim 10^{14}$ G (Thompson & Duncan 1996; Heyl & Hernquist 1997; Melatos 1999). However, the association of the AXP 1E 1841−045 with the very young ($\lesssim$2 kyr) SNR G27.4+0.0 (Vasisht & Gotthelf 1997) makes the case that 1E 1841−045 is a young object. Assuming that the pulsar was born spinning quickly, it is difficult to see how accretion could have slowed it down to its current period in such a short time. This result thus favors the magnetar model for 1E 1841−045, and indeed the magnetic field inferred from its period and period derivative, and assuming standard pulsar spin-down, is $B \approx 8 \times 10^{14}$ G.

AX J1845−0258 (also called AX J1844.8−0258) is a 6.97 s X-ray pulsar, which was found serendipitously in an *ASCA* observation of the (presumably unassociated) SNR G29.7−0.3 (Gotthelf & Vasisht 1998, hereafter GV98; Torii et al. 1998, hereafter T98). The long pulse period, low Galactic latitude, and soft spectrum of AX J1845−0258 led GV98 and T98 to independently propose that this source is an AXP (a conclusion that still needs to be confirmed through measurement of a period derivative). The high hydrogen column density inferred from photoelectric absorption ($N_{\rm H} \approx 10^{23}$ cm^{-2}) suggests that AX J1845−0258 is distant; T98 put it in the Scutum arm, with a consequent distance of 8.5 kpc, while GV98 nominate a distance of 15 kpc.

Because AX J1845−0258 was discovered at the very edge of the *ASCA* gas-imaging spectrometer field of view, its position from these observations could only be crudely estimated, with an uncertainty of ∼3′. A subsequent (1999 March) 50 ks on-axis *ASCA* observation has since been carried out (Vasisht et al. 1999). No pulsations are seen in these data, but a faint point source, AX J184453.3−025642, is detected within the error circle for AX J1845−0258. Vasisht et al. (1999) determine an accurate position for AX J184453.3−025642 and argue that it corresponds to AX J1845−0258 in a quiescent state. Significant variations in the flux density of AX J1845−0258 were also reported by T98.

The region containing AX J1845−0258 has been surveyed at 1.4 GHz as part of the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). An image from this survey shows an ∼5′ shell near the position of the pulsar. Here we report on multifrequency polarimetric observations of this radio shell, at substantially higher sensitivity and spatial resolution than offered by the NVSS. Our observations and analysis are described in § 2, and the resulting images are presented in § 3. In § 4, we argue that the radio shell coincident with AX J1845−0258 is a new SNR and consider the likelihood of an association between the two sources.

2. OBSERVATIONS AND DATA REDUCTION

Radio observations of the field of AX J1845−0258 were made with the D configuration of the Very Large Array (VLA) on 1999 March 26. The total observing time was 6 hr, of which 4.5 hr was spent observing in the 5 GHz band and the remainder in the 8 GHz band. The 5 GHz observations consisted of a 100 MHz bandwidth centered on 4.860 GHz; the 8 GHz observations were similar but centered on 8.460 GHz. Amplitudes were calibrated by observations of 3C 286, assuming flux densities of 7.5 and 5.2 Jy at 5 and 8 GHz, respectively. Antenna gains and instrumental polarization were calibrated using regular observations of MRC 1801+010. Four Stokes parameters (*RR*, *LL*, *RL*, and *LR*) were recorded in all observations. To

[1] Center for Space Research, Massachusetts Institute of Technology, 70 Vassar Street, Cambridge, MA 02139; bmg@space.mit.edu.
[2] Hubble Fellow.
[3] Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027; evg@astro.columbia.edu.
[4] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109; gv@astro.caltech.edu.

TABLE 1
VLA Observations of G29.6+0.1[a]

Parameter	5 GHz	8 GHz
Resolution (arcsec)	12.8 × 12.5	8.2 × 7.5
rms noise (μJy beam^{-1})	100	80
Flux density of G29.6+0.1 (mJy)[b]	410 ± 5	260 ± 10

[a] The center of G29.6+0.1 is at $\alpha = 18^h44^m52^s$, $\delta = -02°56'30''$ (J2000) and $l = 29.57$, $b = +0.12$. The diameter of G29.6+0.1 is 4.′5 × 5.′0.

[b] These flux densities are underestimates, since the largest spatial scales were not well imaged.

cover the entire region of interest, observations were carried out in a mosaic of 2 (3) pointings at 5 (8) GHz.

Data were edited and calibrated in the MIRIAD package. In total intensity (Stokes *I*), mosaic images of the field were formed using uniform weighting and maximum entropy deconvolution. The resulting images were then corrected for both the mean primary-beam response of the VLA antennas and the mosaic pattern. The resolution and noise in the final images are given in Table 1. Images of the region were also formed in Stokes *Q*, *U*, and *V*. These images were made using natural weighting, to give maximum sensitivity, and then deconvolved using a joint maximum entropy technique (Sault, Bock, & Duncan 1999). At each of 5 and 8 GHz, a linear polarization image *L* was formed from *Q* and *U*. Each *L* image was clipped where the polarized emission or the total intensity was less than 5 σ.

In order to determine a spectral index from these data, it is important to ensure that the images contain the same spatial scales. We thus spatially filtered each total intensity image (see Gaensler et al. 1999), removing structure on scales larger than 5′ and smoothing each image to a resolution of 15″. The spatial distribution of spectral index was then determined using the method of temperature-temperature ("*T*-*T*") plots (Turtle et al. 1962; Gaensler et al. 1999).

3. RESULTS

Total intensity images of the region are shown in Figure 1. At both 5 and 8 GHz, a distinct shell of emission is seen, which we designate G29.6+0.1; observed properties are given in Table 1. The shell is clumpy, with a particularly bright clump on its eastern edge. In the east, the shell is quite thick (up to 50% of the radius), while the northwestern rim is brighter and narrower. Two point sources can be seen within the shell interior. At 5 GHz, the shell appears to be sitting on a plateau of diffuse extended emission; this emission is resolved out at 8 GHz.

Significant linear polarization at 5 GHz is seen from much of the shell, particularly in the two brightest parts of the shell on the eastern and western edges. Where detected, the fractional polarization is 2%–20%. At 8 GHz, linear polarization is seen only from these two regions, with 5%–40% fractional polarization. No emission was detected in Stokes *V*, except for instrumental effects associated with the offset of the VLA primary beam between left- and right-circular polarization.

Meaningful *T*-*T* plots were obtained for three regions of the SNR, as marked in Figure 1; the spectral index α ($S_\nu \propto \nu^\alpha$) for each region is marked. There appear to be distinct variations in spectral index around the shell, but all three determinations fall in the range $-0.7 \lesssim \alpha \lesssim -0.4$.

Two point sources are visible within the field. The more northerly of the two is at $18^h44^m55^s.11$, −02°55′36.″9 (J2000) with $S_{5\,\mathrm{GHz}} = 0.8 \pm 0.1$ mJy and $\alpha = 0.5 \pm 0.3$, while the other is at $18^h44^m50^s.59$, −02°57′58.″5 (J2000) with $S_{5\,\mathrm{GHz}} = 2.0 \pm 0.3$ mJy and $\alpha = -0.4 \pm 0.1$. Positional uncertainties for both sources are ≈0.″3 in each coordinate. No emission is detected from either source in Stokes *Q*, *U*, or *V*.

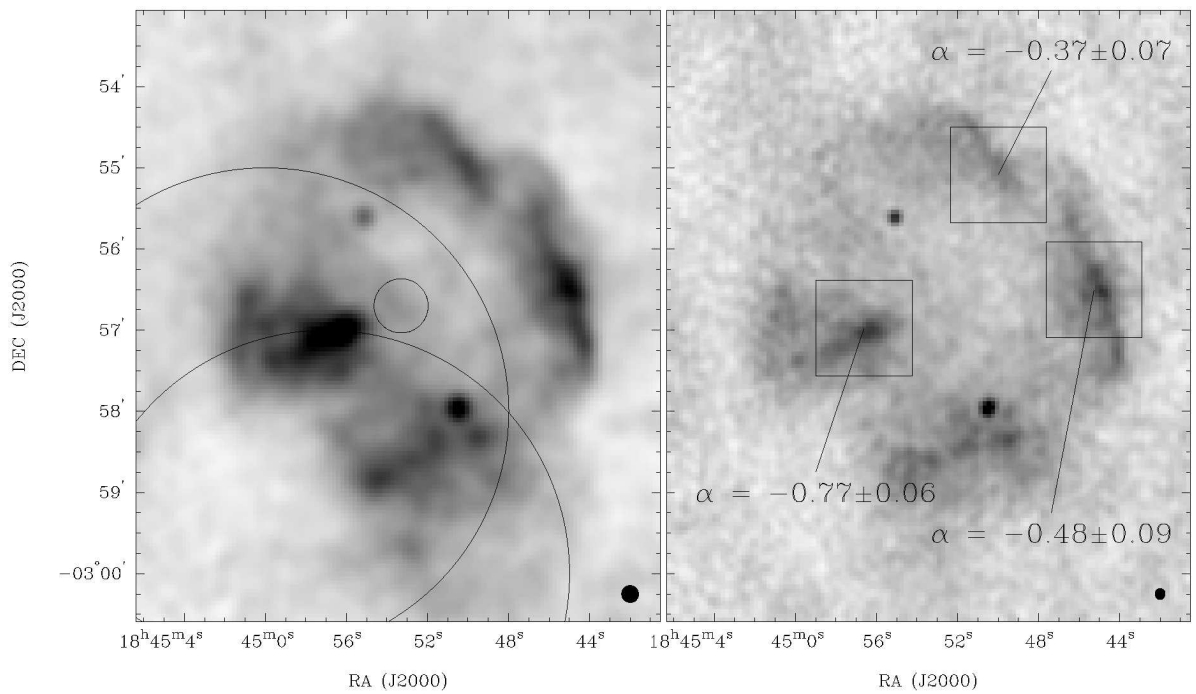

Fig. 1.—VLA images of G29.6+0.1. *Left*: A 5 GHz image, corrected for primary-beam attenuation and shown with a gray-scale range of −0.4 to 2.5 mJy beam^{-1}. The large open circles correspond to the position estimates for AX J1845−0258 of GV98 (*upper circle*) and T98 (*lower circle*), respectively; the small open circle marks the position of AX J184453.3−025642 (Vasisht et al. 1999). *Right*: A 8 GHz image, uncorrected for primary-beam effects; the gray-scale range is −0.2 to 1.3 mJy beam^{-1}. The boxes correspond to regions in which a spectral index, α ($S_\nu \propto \nu^\alpha$), could be calculated. The synthesized beams are shown in the lower right-hand corner.

4. DISCUSSION

The source G29.6+0.1 is significantly linearly polarized and has a nonthermal spectrum. Furthermore, the source has a distinct shell morphology and shows no significant counterpart in 60 μm *IRAS* data. These are all the characteristic properties of supernova remnants (e.g., Whiteoak & Green 1996), and we thus classify G29.6+0.1 as a previously unidentified SNR.

4.1. *Physical Properties of G29.6+0.1*

Distances to SNRs are notoriously difficult to determine. The purported Σ-D relation has extremely large uncertainties, and this source is most likely too faint to show H I absorption. So while we cannot determine a distance to G29.6+0.1 directly, we can attempt to estimate its distance by associating it with other objects in the region. Indeed, hydrogen recombination lines from extended thermal material have been detected from the direction of G29.6+0.1 (Lockman, Pisano, & Howard 1996), at systemic velocities of 42 and 99 km s^{-1}. Adopting a standard model for Galactic rotation (Fich, Blitz, & Stark 1989), these velocities correspond to possible distances of 3, 6, 9, or 12 kpc, a result that is not particularly constraining.

Nevertheless, G29.6+0.1 is of sufficiently small angular size that we can put an upper limit on its age simply by assuming that it is located within the Galaxy. At a maximum distance of 20 kpc, the SNR is 27.5 $\pm$ 1.5 pc across. For a uniform ambient medium of density n_0 cm^{-3}, the SNR has then swept up $(260 \pm 40) n_0\, M_\odot$ from the interstellar medium (ISM) that, for typical ejected masses and ambient densities, corresponds to a SNR that has almost completed the transition from free expansion to the adiabatic (Sedov-Taylor) phase (see, e.g., Dohm-Palmer & Jones 1996). Thus, expansion in the adiabatic phase acts as an upper limit, and we can derive a maximum age for G29.6+0.1 of $(13 \pm 4)\,(n_0/E_{51})^{1/2}$ kyr, where E_{51} is the kinetic energy of the explosion in units of 10^{51} ergs. For a typical value of $n_0/E_{51} = 0.2$ (Frail, Goss, & Whiteoak 1994), we find that the age of the SNR must be less than 8 kyr. For distances nearer than 20 kpc, the SNR is even younger. For example, at a distance of 10 kpc, the SNR has swept up sufficiently little material from the ISM that it is still freely expanding, and an expansion velocity 5000 km s^{-1} then corresponds to an age of 1.4 kyr.

4.2. *An Association with AX J1845−0258?*

G29.6+0.1 is a young SNR in the vicinity of a slow X-ray pulsar. If the two can be shown to be associated, and if we assume that AX J1845−0258 was born spinning rapidly, then the youth of the system argues that AX J1845−0258 has slowed down to its current period via electromagnetic braking rather than via the accretion torque and that it is thus best interpreted as a magnetar (cf. Vasisht & Gotthelf 1997). Indeed, if one assumes that the source has slowed down through the former process, its inferred dipole magnetic field is $\sim 9 t_3^{-1/2} \times 10^{14}$ G, for an age of t_3 kyr. For ages in the range of 1.4–8 kyr (see § 4.1), this results in a field in the range of (3–8) $\times$ 10^{14} G, which is typical of other sources claimed to be magnetars.

But are the two sources associated? Associations between neutron stars and SNRs are judged on various criteria, including agreements in distance and in age, positional coincidence, and evidence for interaction. Age and distance are the most fundamental of these, but unfortunately existing data on AX J1845−0258 provide no constraints on an age and suggest only a very approximate distance of ~10 kpc (GV98; T98).

The source AX J184453.3−025642 (Vasisht et al. 1999) is located well within the confines of G29.6+0.1, less than 40″ from the center of the remnant (see Fig. 1). Vasisht et al. (1999) argue that AX J1845−0258 and AX J184453.3−025642 are the same source; if we assume that this source is associated with the SNR and was born at the remnant's center, then we can infer an upper limit on its transverse velocity of $1900 d_{10}/t_3$ km s^{-1}, where the distance to the system is $10 d_{10}$ kpc. In § 4.1, we estimated $d_{10}/t_3 \sim 0.3$–0.7, and so the velocity inferred falls comfortably within the range seen for the radio pulsar population (e.g., Lyne & Lorimer 1994; Cordes & Chernoff 1998) Alternatively, if we assume a transverse velocity of $400 v_{400}$ km s^{-1}, we can infer an age for the system of less than $5 d_{10}/v_{400}$ kyr, which is consistent with the determinations above. There is no obvious radio counterpart to the X-ray pulsar—both radio point sources in the region are outside all of the X-ray error circles. At the position of AX J184453.3−025642, we set a 5 σ upper limit of 1 mJy on the 5 GHz flux density of any point source.

We also need to consider the possibility that the positional alignment of AX J184453.3−025642 and G29.6+0.1 is simply by chance. The region is a complex part of the Galactic plane—there are 15 cataloged SNRs within 5°—and it seems reasonable in such a region that unassociated SNRs and neutron stars could lie along the same line of sight (Gaensler & Johnston 1995). Many young radio pulsars have no associated SNR (Braun, Goss, & Lyne 1989), so there is no reason to demand that even a young neutron star be associated with a SNR.

The first quadrant of the Galaxy is not well surveyed for SNRs, so we estimate the likelihood of a chance association by considering the fourth quadrant, which has been thoroughly surveyed for SNRs by Whiteoak & Green (1996) In a representative region of the sky defined by $320° \le l \le 355°$ and $|b| \le 1.^\circ 5$, we find 44 SNRs in their catalog. Thus, for the ~10 radio-quiet neutron stars, AXPs and SGRs at comparable longitudes and latitudes, there is a probability of 1.6×10^{-3} that at least one will lie within 40″ of the center of a known SNR by chance. Of course, in the present case, we have carried out a targeted search toward a given position, and so the probability of spatial coincidence is somewhat higher than for a survey; nevertheless, we regard it unlikely that AX J184453.3−025642 should lie so close to the center of an unrelated SNR, and hence we propose that the pulsar and the SNR are genuinely associated.

There is good evidence that magnetars power radio synchrotron nebulae through the injection of relativistic particles into their environment (Kulkarni et al. 1994; Frail, Kulkarni, & Bloom 1999). The two such sources known are filled-center nebulae with spectral indices $\alpha \sim -0.7$, and in one case the neutron star is substantially offset from the core of its associated nebula (Hurley et al. 1999). In Figure 1, the clump of emission with a peak at $18^{\rm h}44^{\rm m}56^{\rm s}$, $-02°57'$ (J2000) has such properties, and one can speculate that it corresponds to such a source. Alternatively, compact steep-spectrum features are seen in other shell SNRs and may be indicative of deceleration of the shock in regions where it is expanding into a dense ambient medium (Dubner et al. 1991; Gaensler et al. 1999).

5. CONCLUSIONS

Radio observations of the field of the slow X-ray pulsar AX J1845−0258 reveal a linearly polarized nonthermal shell, G29.6+0.1, which we classify as a previously undiscovered supernova remnant. We infer that G29.6+0.1 is young, with an upper limit on its age of 8000 yr. The proposed quiescent counterpart of AX J1845−0258, AX J184453.3−025642, is

almost at the center of G29.6+0.1, from which we argue that the pulsar and SNR were created in the same supernova explosion. The young age of the system provides further evidence that anomalous X-ray pulsars are isolated magnetars rather than accreting systems, although we caution that the apparent flux variability of AX J1845−0258 raises questions concerning both its classification as an AXP and its positional coincidence with G29.6+0.1. Future X-ray measurements should be able to clarify the situation.

There are now six known AXPs, three of which have been associated with SNRs. In every case, the pulsar is at or near the geometric center of its SNR. This result is certainly consistent with AXPs being young, isolated neutron stars, as argued by the magnetar hypothesis. If one considers the radio pulsar population, the fraction of pulsars younger than a given age that can be convincingly associated with SNRs drops as the age threshold increases. The age below which 50% of pulsars have good SNR associations is ~20 kyr, and for several of these, the pulsar is significantly offset from the center of its SNR (e.g., Frail & Kulkarni 1991; Frail et al. 1996). Thus, if the SNRs associated with both AXPs and radio pulsars come from similar explosions and evolve into similar environments, this seems to be good evidence that AXPs are considerably younger than 20 kyr. Indeed, all of the three SNRs associated with AXPs have ages less than 10 kyr (Gotthelf & Vasisht 1997; Parmar et al. 1998; § 4.1 of this Letter). While the sample of AXPs is no doubt incomplete, this implies a Galactic birthrate for AXPs of greater than 0.6 kyr^{-1}. This corresponds to 5% ± 2% of core-collapse supernovae (Cappellaro et al. 1997) or 3%–20% of the radio pulsar population (Lyne et al. 1998; Brazier & Johnston 1999).

There is mounting evidence that SGRs are also magnetars (Kouveliotou et al. 1999). However, of the four known SGRs, two (0526−66 and 1627−41) are on the edge of young SNRs (Cline et al. 1982; Smith, Bradt, & Levine 1999), a third (1900+14) is on the edge of an old SNR (Vasisht et al. 1994), and the fourth (1806−20) has no associated SNR blast wave (Kulkarni et al. 1994). This suggests that SGRs represent an older, or higher velocity, manifestation of neutron stars than do AXPs.

B. M. G. thanks Bob Sault for advice on calibration. The VLA is a facility of the National Radio Astronomy Observatory which is operated by Associated Universities, Inc., under contract with the National Science Foundation. B. M. G. acknowledges the support of NASA through Hubble Fellowship grant HF-01107.01-98A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS5-26555. E. V. G. and G. V.'s research is supported by NASA LTSA grant NAG5-22250.

REFERENCES

Braun, R., Goss, W. M., & Lyne, A. G. 1989, ApJ, 340, 355
Brazier, K. T. S., & Johnston, S. 1999, MNRAS, 305, 671
Cappellaro, E., Turatto, M., Tsvetkov, D. Y., Bartunov, O. S., Pollas, C., Evans, R., & Hamuy, M. 1997, A&A, 322, 431
Cline, T. L., et al. 1982, ApJ, 255, L45
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
Cordes, J. M., & Chernoff, D. F. 1998, ApJ, 505, 315
Dohm-Palmer, R. C., & Jones, T. W. 1996, ApJ, 471, 279
Dubner, G. M., Braun, R., Winkler, P. F., & Goss, W. M. 1991, AJ, 101, 1466
Fich, M., Blitz, L., & Stark, A. A. 1989, ApJ, 342, 272
Frail, D. A., Giacani, E. B., Goss, W. M., & Dubner, G. 1996, ApJ, 464, L165
Frail, D. A., Goss, W. M., & Whiteoak, J. B. Z. 1994, ApJ, 437, 781
Frail, D. A., & Kulkarni, S. R. 1991, Nature, 352, 785
Frail, D. A., Kulkarni, S. R., & Bloom, J. S. 1999, Nature, 398, 127
Gaensler, B. M., Brazier, K. T. S., Manchester, R. N., Johnston, S., & Green, A. J. 1999, MNRAS, 305, 724
Gaensler, B. M., & Johnston, S. 1995, MNRAS, 277, 1243
Ghosh, P., Angelini, L., & White, N. E. 1997, ApJ, 478, 713
Gotthelf, E. V., & Vasisht, G. 1997, ApJ, 486, L133
———. 1998, NewA, 3, 293 (GV98)
Heyl, J. S., & Hernquist, L. 1997, ApJ, 489, L67
Hurley, K., Kouvelioutou, C., Cline, T., Mazets, E., Golenetskii, S., Frederiks, D. D., & van Paradijs, J. 1999, ApJ, 523, L37
Kouveliotou, C. 1999, BAAS, 193, 56.02
Kouveliotou, C., et al. 1999, ApJ, 510, L115
Kulkarni, S. R., Frail, D. A., Kassim, N. E., Murakami, T., & Vasisht, G. 1994, Nature, 368, 129
Lockman, F. J., Pisano, D. J., & Howard, G. J. 1996, ApJ, 472, 173
Lyne, A. G., & Lorimer, D. R. 1994, Nature, 369, 127
Lyne, A. G., et al. 1998, MNRAS, 295, 743
Melatos, A. 1999, ApJ, 519, L77
Mereghetti, S. 1999, Mem. Soc. Astron. Italiana, 69, 819
Mereghetti, S., & Stella, L. 1995, ApJ, 442, L17
Parmar, A. N., Oosterbroek, T., Favata, F., Pightling, S., Coe, M. J., Mereghetti, S., & Israel, G. L. 1998, A&A, 330, 175
Sault, R. J., Bock, D. C. J., & Duncan, A. R. 1999, A&AS, in press
Smith, D. A., Bradt, H. V., & Levine, A. M. 1999, ApJ, 519, L147
Thompson, C., & Duncan, R. C. 1996, ApJ, 473, 322
Torii, K., Kinugasa, K., Katayama, K., Tsunemi, H., & Yamauchi, S. 1998, ApJ, 503, 843 (T98)
Turtle, A. J., Pugh, J. F., Kenderdine, S., & Pauliny-Toth, I. I. K. 1962, MNRAS, 124, 297
van Paradijs, J., Taam, R. E., & van den Heuvel, E. P. J. 1995, A&A, 299, L41
Vasisht, G., & Gotthelf, E. V. 1997, ApJ, 486, L129
Vasisht, G., Gotthelf, E. V., Torii, K., & Gaensler, B. M. 1999, ApJ, submitted
Vasisht, G., Kulkarni, S. R., Frail, D. A., & Greiner, J. 1994, ApJ, 431, L35
Whiteoak, J. B. Z., & Green, A. J. 1996, A&AS, 118, 329